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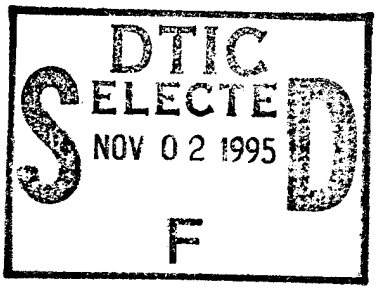
High-Frequency Surface-Scattering Measurements During the *FLIP* Experiment

by Peter H. Dahl



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Contents

1. INTRODUCTION 1

2. MEASUREMENT TECHNIQUE AND DATA PROCESSING 1

3. EXPERIMENTAL RESULTS 3

4. SUMMARY 4

5. REFERENCES 5

List of Figures

1. Experimental layout for measurements of surface backscattering strength from the research platform *FLIP*. 6

2. Launch and surface-grazing angles (relative to horizontal) vs two-way travel time for run B265. 7

3. Comparison of measured and modeled surface-backscattering strengths at 20–50 kHz. 8

4a. Comparison of measured and modeled surface backscattering strengths at 20–50 kHz. 9

4b. Expanded scale for Figure 4a. 10

5. Comparison of measured and modeled surface backscattering strengths at 25 kHz. 11

6. Comparison of measured and modeled surface backscattering strengths at 27 kHz. 12

7a. Comparison of measured and modeled surface backscattering strengths at 30 and 40 kHz. 13

7b. Expanded scale for Figure 7a. 14

8a. Comparison of measured and modeled surface backscattering strengths at 30 and 40 kHz. 15

8b. Expanded scale for Figure 8a. 16

9a. Comparison of measured and modeled surface backscattering strengths at 30 kHz. 17

9b. Expanded scale for Figure 9a. 18

10. Comparison of measured and modeled surface backscattering strengths vs wind speed at a grazing angle of $2° \pm 1°$. 19

11. Comparison of measured and modeled surface backscattering strengths vs wind speed at a grazing angle of $4° \pm 1°$. 20

12. Comparison of measured and modeled surface backscattering strengths vs wind speed at a grazing angle of $8° \pm 1°$. 21

13. Comparison of measured and modeled surface backscattering strengths vs wind speed at a grazing angle of $10° \pm 1°$. 22

ABSTRACT

Several kinds of high-frequency surface-scattering measurements and environmental sea-state measurements were made from the research platform *FLIP* in January 1992. Data from this experiment continue to be used in the research and development of models that predict performance of high-frequency sonar systems. This report summarizes results of sea-surface-backscattering measurements obtained over the frequency range 20–50 kHz and the grazing-angle interval 1–15° for wind speeds between 1 and 10 m/s. This low-grazing-angle interval represents an important gap in our database of sea-surface-backscattering strength used in modeling. One data set was also obtained over the grazing-angle interval 35–55° during which the wind speed was 4.6 m/s. The data compare reasonably well with the APL-UW surface-backscattering model for the frequency range 25–40 kHz. At 20 and 50 kHz, however, the data are consistently lower (by 2–4 dB) than the model. A bias in the 20- and 50-kHz data, which is associated with the frequency response of the transducer system, is strongly suspected. Overall, the model fits the *FLIP* data to within a mean error (for the model-minus-data vector) of 1.7 dB and a standard deviation of 2.7 dB. When the 20- and 50-kHz data are corrected for bias, the mean error is reduced to 0.8 dB.

1. INTRODUCTION

This report summarizes the results of sea-surface-backscattering measurements conducted from R/P *FLIP* during January 1992. The experiment consisted of a set of high-frequency acoustic measurements that fall into three basic categories: forward scattering,[1–3] vertical-incidence scattering from bubbles,[4] and sea-surface backscattering. Information about the general experimental conditions and the environmental measurements made during the experiment is available in Refs. 1–4. Results of the *FLIP* experiment continue to be used in the development and improvement of sonar models that apply to operating conditions imposed by the near-surface environment. These models are used in designing, simulating, and predicting the performance of high-frequency sonar systems.

The results of this particular work will be placed into the Applied Physics Laboratory's database of sea-surface backscattering strength as a function of frequency, grazing angle, and wind speed or other sea-state descriptor. The new data reported here are compared with the most recent version of this model, which is discussed in Ref. 5.

2. MEASUREMENT TECHNIQUE AND DATA PROCESSING

Figure 1 shows the measurement geometry. A modified Mk 46 array was mounted on *FLIP*'s hull at a depth of 66 m. The array's pitch angle was controlled remotely, and could be changed from 2.5 to 45°; the instantaneous value of this angle was also recorded for each ping. CW pulses were transmitted either in a single-pulse sequence or in a multifrequency sequence during which the frequency changed from 20 to 50 kHz in 10-kHz steps. An experimental run consisted of 20–25 pings at a given frequency transmitted at 2- to 4-s intervals.

The array used in these measurements is divided into four subbeams; the array transmitted as a single beam, and the signals received from each of the four subbeams were recorded separately. The received signals were heterodyned to 5 kHz and digitized at a 20-kHz rate. For computing scattering strength, signals from the four subbeams were coherently recombined, and the beam pattern from this sum beam was used in the calculations.

A preliminary step in the processing is to combine two subbeams into top-half and bottom-half beams, referred to as split beams. This step is crucial as it allows estimation of the phase angle between the two split beams, which is converted to the arrival/launch angle.[6] This launch angle may differ significantly from the surface-grazing angle. To find an equivalence between the two, we use the Generic Sonar

Model (GSM) ray-based propagation program[7] together with data from the most concurrent CTD cast to produce synthetic launch and surface-grazing angles (Figure 2). We expect good agreement between the synthetic launch angles and those estimated using the split-beam procedure, as shown in Figure 2. Then the synthetic surface-grazing angle computed from GSM is taken to be the estimate of surface-grazing angle θ used in the scattering-strength calculations.

Final estimates of scattering strength are obtained by solving the sonar equation,

$$SS = RL - SL + 30\log R + 2\alpha R - 10\log(c\tau/2) - SRI(\theta); \qquad (1)$$

where

SS	=	surface backscattering strength, dB
RL	=	received reverberation level, dB re 1 μPa
SL	=	source level, dB re 1 μPa at 1 m
R	=	slant range, m
α	=	absorption loss, dB/m
c	=	speed of sound, m/s
τ	=	transmitted pulse length, s
$SRI(\theta)$	=	surface reverberation index, which accounts for the two-way beam-pattern loss.[6]

Note that $30\log R - SRI$ equals $40\log R - 10\log A$, where A is the area responsible for the surface scattering. We thus assume two-way spherical spreading ($40\log R$) applies in Eq. (1). This assumption is again checked with the GSM propagation model.

A ± 3 dB error band should be assumed for all the scattering strength measurements. This estimate is based on the following rough estimates for error components:

Uncertainty in two-way absorption loss	± 1 dB
The standard error about the mean SS estimate based on 20 pings	± 1 dB
Uncertainty in the field estimate of SL	± 1 dB.

We assume no error in the geometric transmission loss (spherical spreading) and in the estimates for the system calibration constants.

We have evidence of a bias in the system calibration constants for the measurements taken at 20 and 50 kHz. The likely reason is that at 20 and 50 kHz the transmitting and receiving sensitivities for the modified Mk 46 array are rolling off, whereas at the center frequencies, in the 25–40 kHz range, the sensitivities are relatively independent of frequency. Because of this rolloff, we surmise that the frequency

response at 20 and 50 kHz was more sensitive to changes in the temperature and pressure conditions relative to those that existed during the calibrations made before and after the experiment. Unfortunately, we cannot measure this bias because it would require recalibration of the system at the operational depth of 66 m. However, a bias estimate derived from the data is approximately -2 dB for the 20-kHz data and approximately -4 dB for the 50-kHz data; that is, the 20- and 50-kHz scattering-strength data should be raised by 2 and 4 dB, respectively. The bias estimates are discussed further in the next section.

3. EXPERIMENTAL RESULTS

Figure 3 shows the frequency dependence of the data for wind speeds between 5.7 and 6.2 m/s and a grazing angle of 4°. Model results are shown as lines; the upper line is the prediction when using a wind speed of 6.2 m/s, and the lower line is the prediction when using a wind speed of 5.7 m/s. The 20- and 50-kHz data appear low, both relative to the model and to the 30- and 40-kHz data, by approximately 2 dB and 5 dB, respectively. We know of no theoretical reason, nor any empirical evidence shown in past data, to indicate surface scattering at both 20 and 50 kHz would be lower than scattering at the range of frequencies in between. We therefore attribute these results to a likely bias in the calibration values for 20 and 50 kHz.

Figures 4a and 4b show the angular dependence of the data for a wind speed of 4.6 m/s. This is a single run in which the array pitch angle was set to 45° to measure backscatter at high angles. The solid line is the model prediction for 20 kHz, and the dashed line is the prediction for 50 kHz, both for a wind speed of 4.6 m/s. Overall, the model fit to the data is quite good, but again the 20- and 50-kHz data are depressed, this time by approximately 2 and 3 dB, respectively.

Figures 5–9 show the angular dependence of the data in the 0–10° range for various wind speeds and frequencies between 25 and 40 kHz. The model does a generally good job of predicting the data, particularly if a spread of ± 1 m/s about the actual measured wind speed is used in the simulation, as recommended[5] for wind speeds <8 m/s. In this range, the air-sea interface is typically more sensitive to small changes in wind speed, making model predictions based on wind speed alone more difficult. In Figure 6, for example, the model is slightly higher than the data (though an adjustment of only 0.5 m/s is needed to bring the model more in line), while in Figure 8 the model is lower, particularly for the measurements at 40 kHz.

The measurements shown in Figures 7 and 8 were taken within 30 min of each other, and their grazing-angle dependence is markedly different (c.f. Figures 7b and

8b). In Figure 7b, it is tempting to "shift" the model about 2° to the right—giving a nearly perfect fit for both level and angular dependence. Unfortunately, what is shown is the result of our best estimate of the surface-grazing angle using a combination of the split-beam procedure and the GSM model. Our grazing-angle estimates are likely correct, and the data in Figure 7b simply roll off approximately 2° earlier than what the model predicts. The data in Figure 8b, on the other hand, show a very different angular dependence. One should view Figures 7b and 8b as representative of the potential variation in surface scattering strength for very similar conditions.

The wind-speed dependence of the data for a fixed grazing angle is shown in Figures 10–13. The figures were generated by collecting all data that lie between the grazing-angle bounds given at the top of each figure (with the upper bound inclusive). The lines are the model estimates for 20, 30, and 50 kHz. The data* generally support the wind-speed trends given by the model, although the wind-speed range is small, being mostly confined to $\leq$6.5 m/s with a few values near 10 m/s.

4. SUMMARY

Table 1 summarizes the performance of the model in predicting the results of the 1992 *FLIP* surface-backscattering measurements. Performance is quantified in terms of the mean and standard deviation of the model-minus-data vector, where both model and data are expressed in decibels. The data are grouped into two grazing-angle ranges (1–15° and 35–55°) and three frequency intervals (20 kHz, 25–40 kHz, and 50 kHz). Note that, unlike in the previous figures, here we have corrected for the

Table 1. Mean and standard deviation (in parentheses) of the model-minus-data error, expressed in decibels, for three angular intervals.

Angular Range (deg)	Frequency Interval (kHz)		
	20	25–40	50
0–15	0.7(2.1)	1.8(3.0)	2.3(2.5)
35–55	−0.8(1.0)	−0.2(1.3)	−1.4(1.2)
All data	0.8(2.6)		

*As in Figures 3 and 4, the 20- and 50-kHz data have not been corrected for their estimated biases.

estimated bias in the 20- and 50-kHz data by adding 2 dB and 4 dB, respectively, to these data. The mean and standard deviation of the error for all the data are 0.8 and 2.6 dB, respectively. When the original 20- and 50-kHz data (uncorrected for bias) are used, these values are 1.7 and 2.7 dB, respectively.

Finally, we emphasize that the model used wind-speed measurements made from *FLIP* at a height of 10 m above the sea surface (the standard height for wind-speed measurements at sea). If the model were run using wind-speed values measured at heights greater than 10 m, it would likely give *greater* scattering-strength estimates and appear to be biased on the high side. For example, the difference between the wind-speed measurements made at 25 m and 10 m during the *FLIP* experiment ranged between 0.2 and 0.8 m/s (this difference generally increases with increasing wind speed), with an average difference of approximately 0.35 m/s. As can be seen in Figures 10–13 for wind speeds less than about 8 m/s, an increase in wind speed of only 0.35 m/s yields an increase of about 1 dB in scattering strength in the model estimates.

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5. APL-UW High Frequency Ocean Environmental Acoustic Models Handbook," APL-UW TR 9407, Applied Physics Laboratory, University of Washington, October 1994.

6. D. R. Jackson, A. M. Baird, J. J. Crisp, and P. A. G. Thomson, "High-frequency bottom scatter measurements in shallow water," *J. Acoust. Soc. Am., 80*, 1188–1199, 1986.

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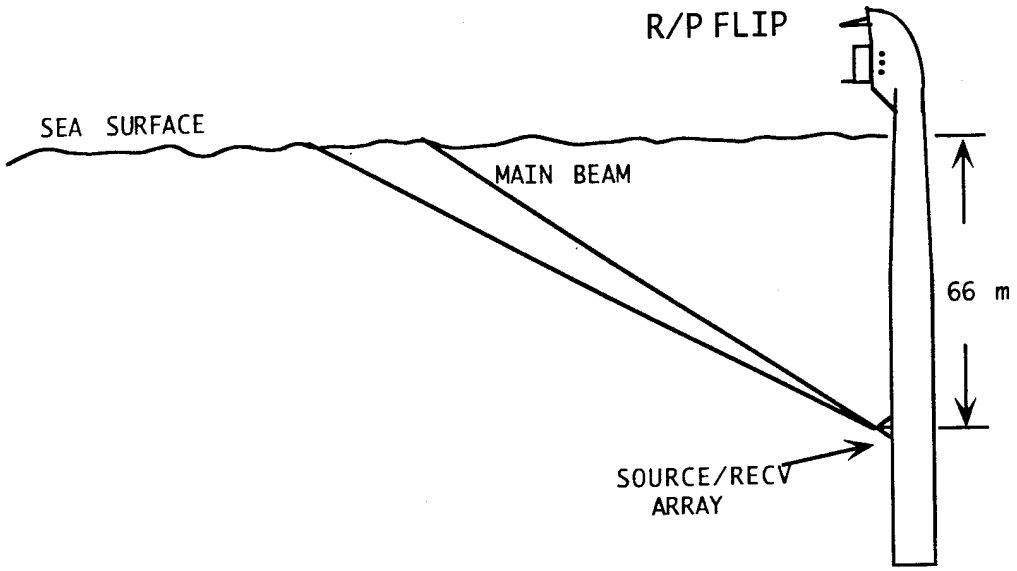

Figure 1. Experimental layout for measurements of surface backscattering strength from the research platform *FLIP*.

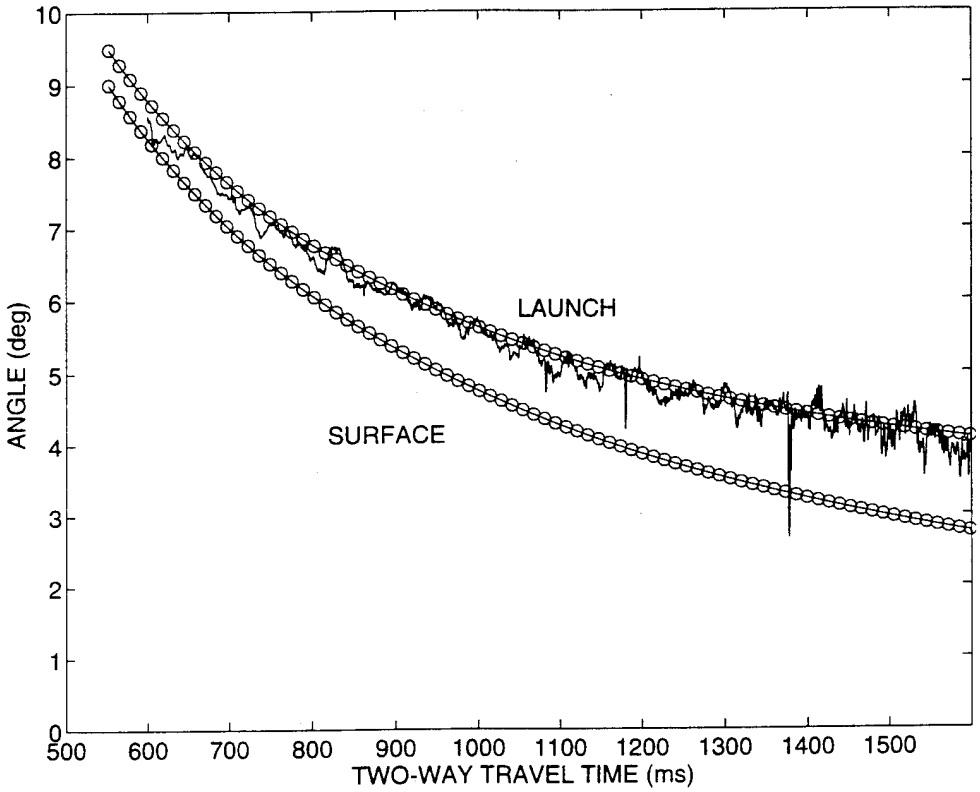

Figure 2. Launch and surface-grazing angles (relative to horizontal) vs two-way travel time for run B265. The circles are computed with the GSM model using CTD data taken most concurrently with the run. The thin line that tracks the GSM launch angle is the equivalent angle estimated from the data via the split-beam procedure. Beyond approximately 1600 ms, the signal-to-noise ratio on this run was poor, and phase tracking was essentially lost.

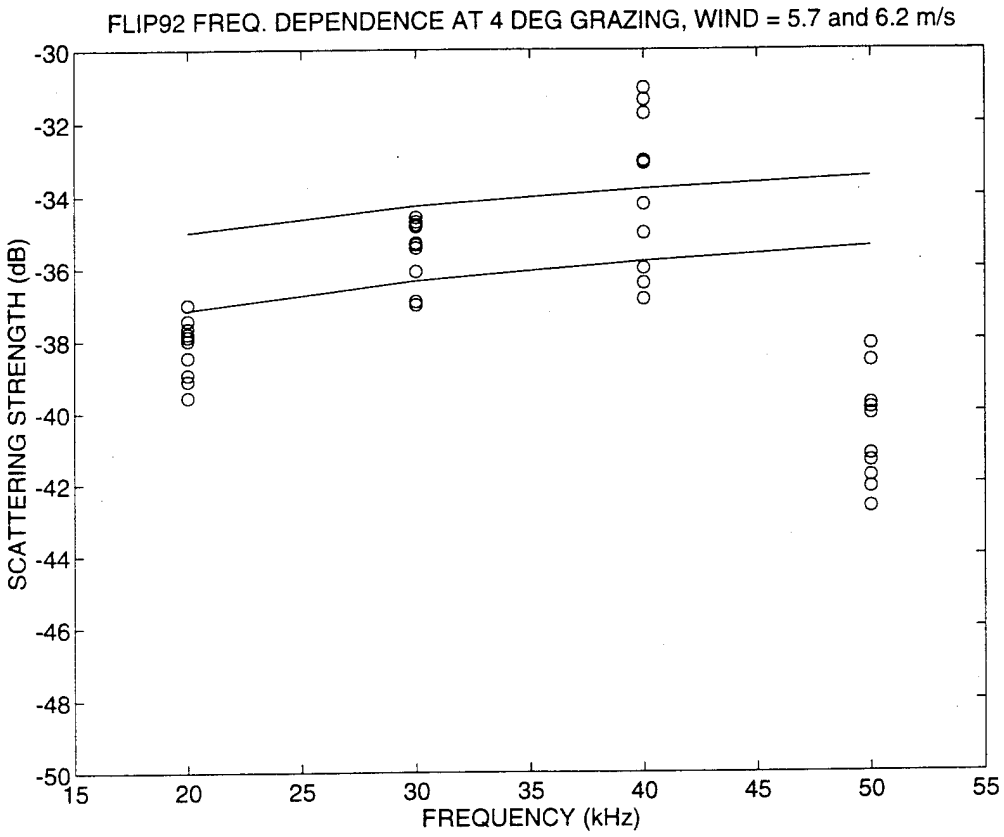

Figure 3. Comparison of measured and modeled surface-backscattering strengths at 20–50 kHz. Circles are data from runs at wind speeds of 5.7–6.2 m/s and a grazing angle of 4°. Upper and lower lines are model predictions for wind speeds of 6.2 and 5.7 m/s respectively.

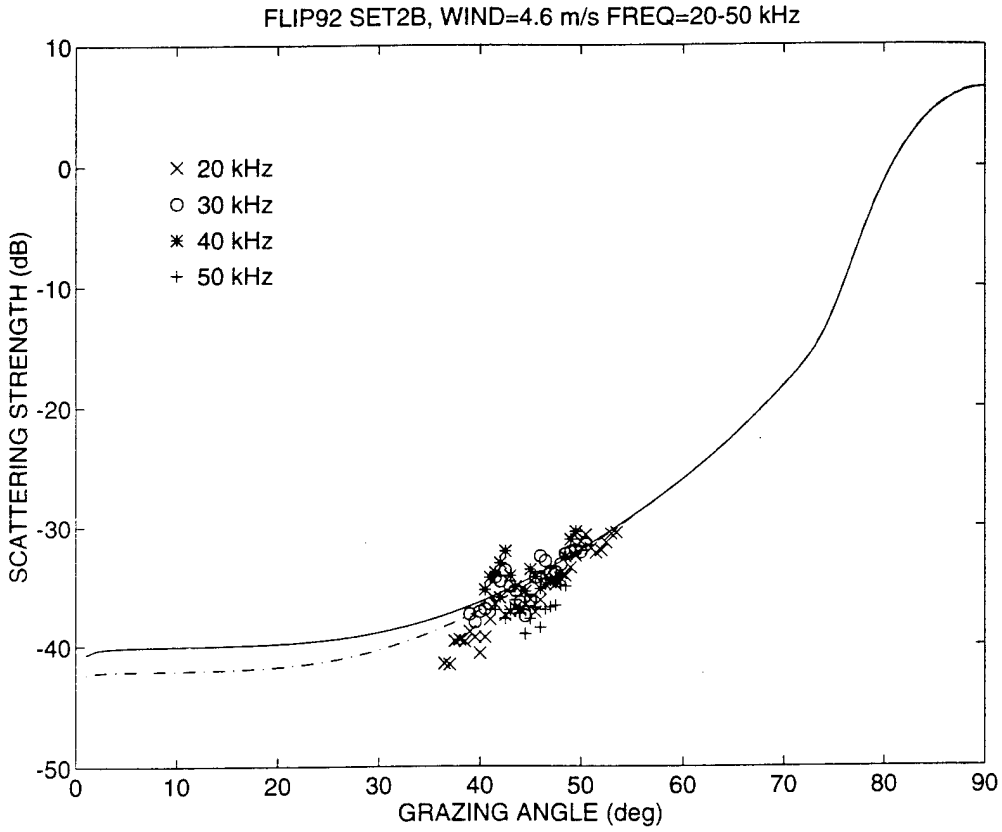

Figure 4a. Comparison of measured and modeled surface backscattering strengths at 20–50 kHz. Data are from one run during which the wind speed was 4.6 m/s. The solid line is the model estimate at 20 kHz, and the dashed line is the estimate at 50 kHz, both for a wind speed of 4.6 m/s.

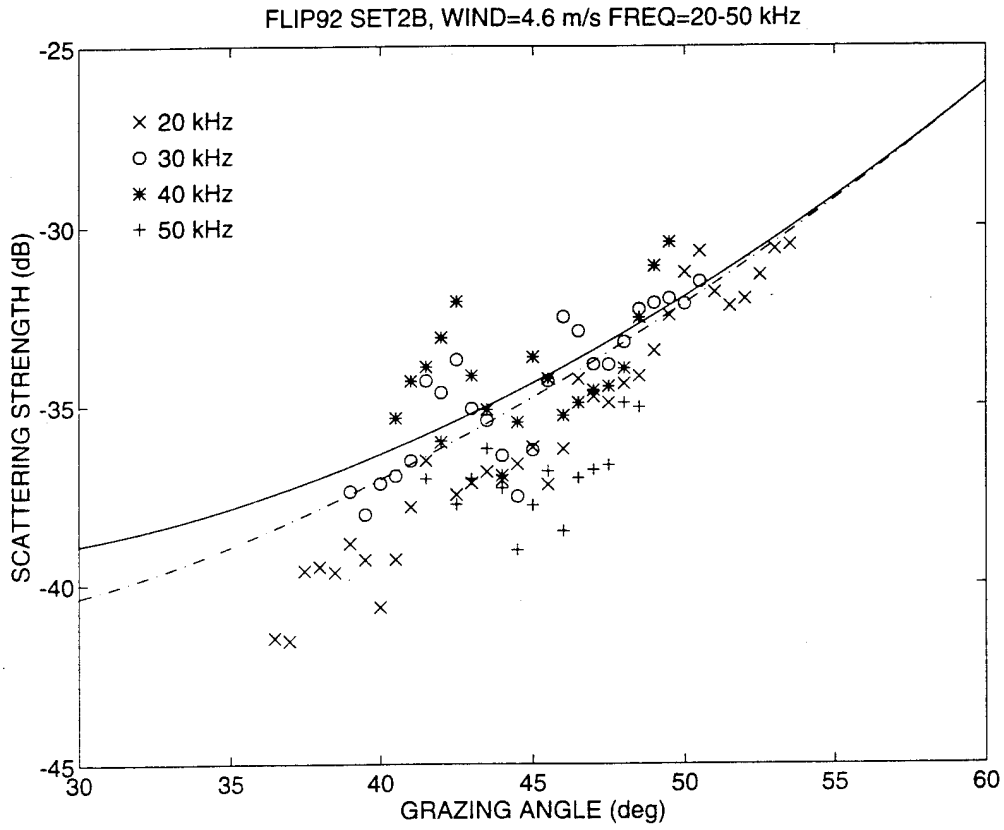

Figure 4b. Expanded scale for Figure 4a.

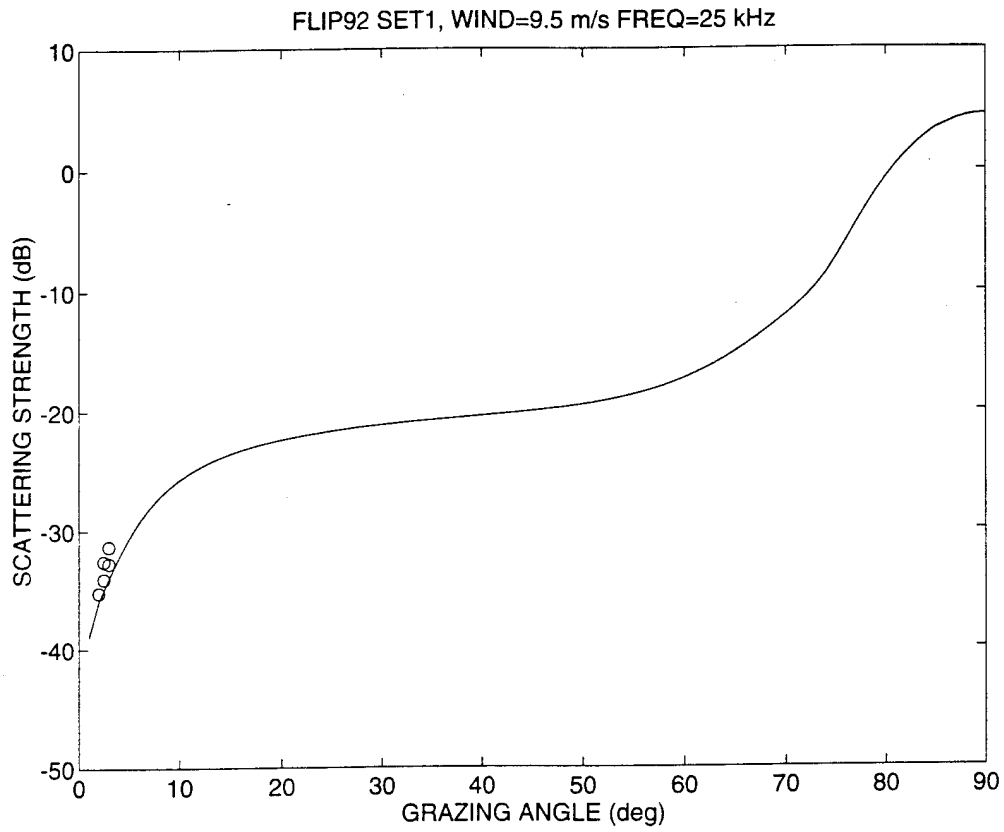

Figure 5. Comparison of measured and modeled surface backscattering strengths at 25 kHz. Data are from two runs during which the wind speed was 9.2 and 9.8 m/s. The solid line is the model estimate for a mean wind speed of 9.5 m/s.

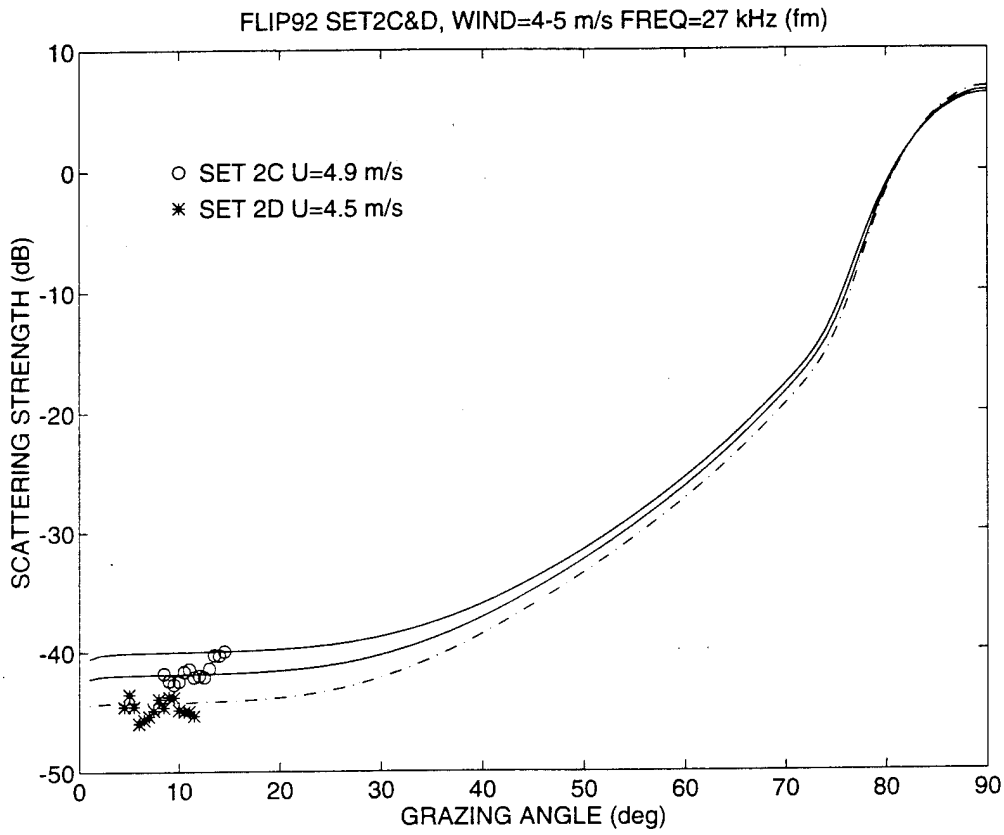

Figure 6. Comparison of measured and modeled surface backscattering strengths at 27 kHz. Data are from two runs during which the wind speed was 4.5 and 4.8 m/s. The two solid lines are the model estimates for the same wind speeds (lower line is 4.5 m/s; upper is 4.8 m/s), and the dashed line is the model estimate for a wind speed of 4.0 m/s.

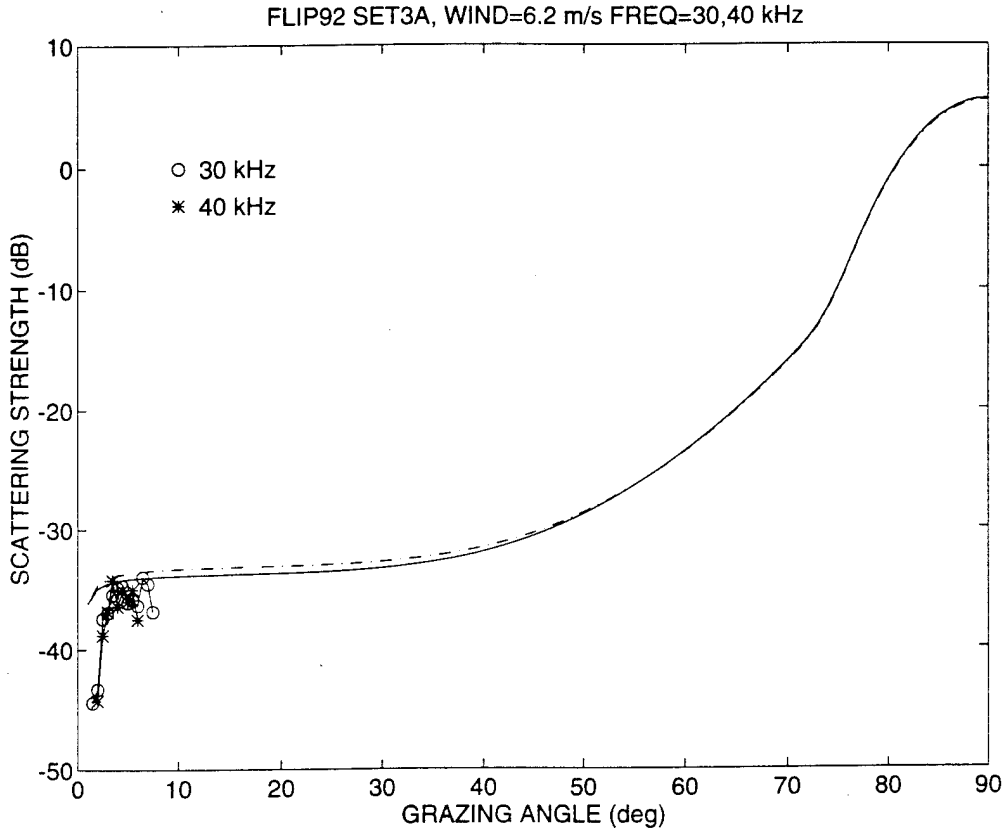

Figure 7a. Comparison of measured and modeled surface backscattering strengths at 30 and 40 kHz. Data are from one run during which the wind speed was 6.2 m/s. The solid line is the model estimate at 30 kHz, and the dashed line is the model estimate at 40 kHz, both for a wind speed of 6.2 m/s.

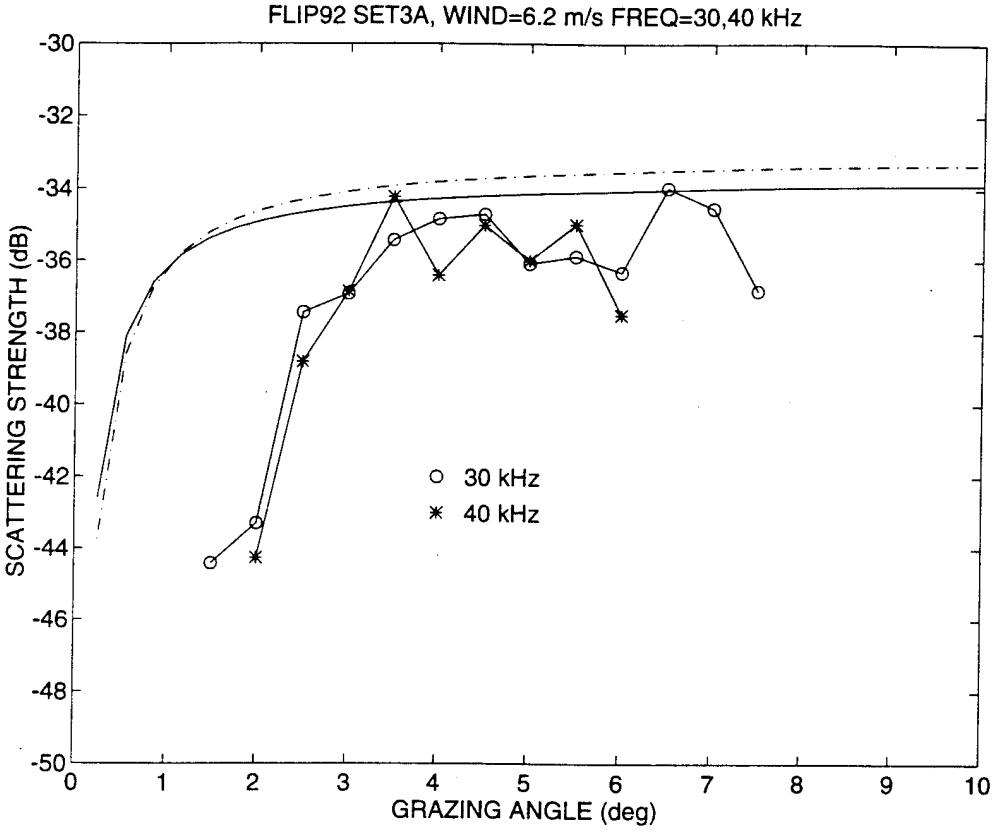

Figure 7b. Expanded scale for Figure 7a.

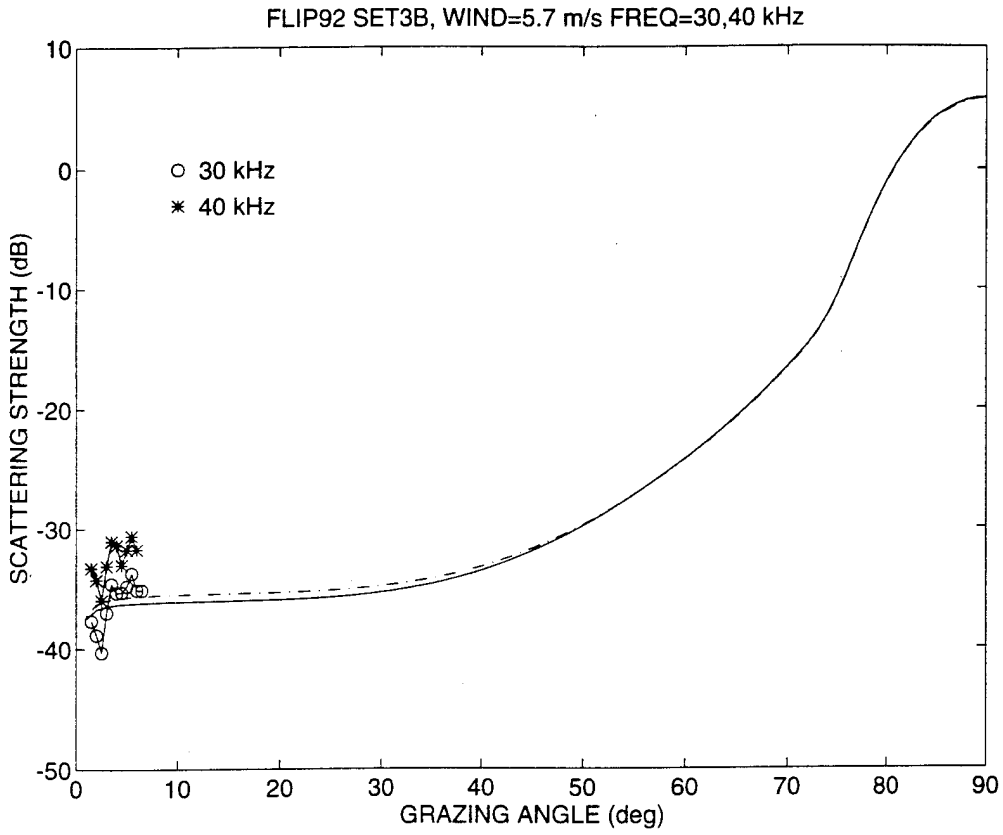

Figure 8a. Comparison of measured and modeled surface backscattering strengths at 30 and 40 kHz. Data are from one run during which the wind speed was 5.7 m/s. The solid line is the model estimate at 30 kHz, and the dashed line is the model estimate at 40 kHz, both for a wind speed of 5.7 m/s.

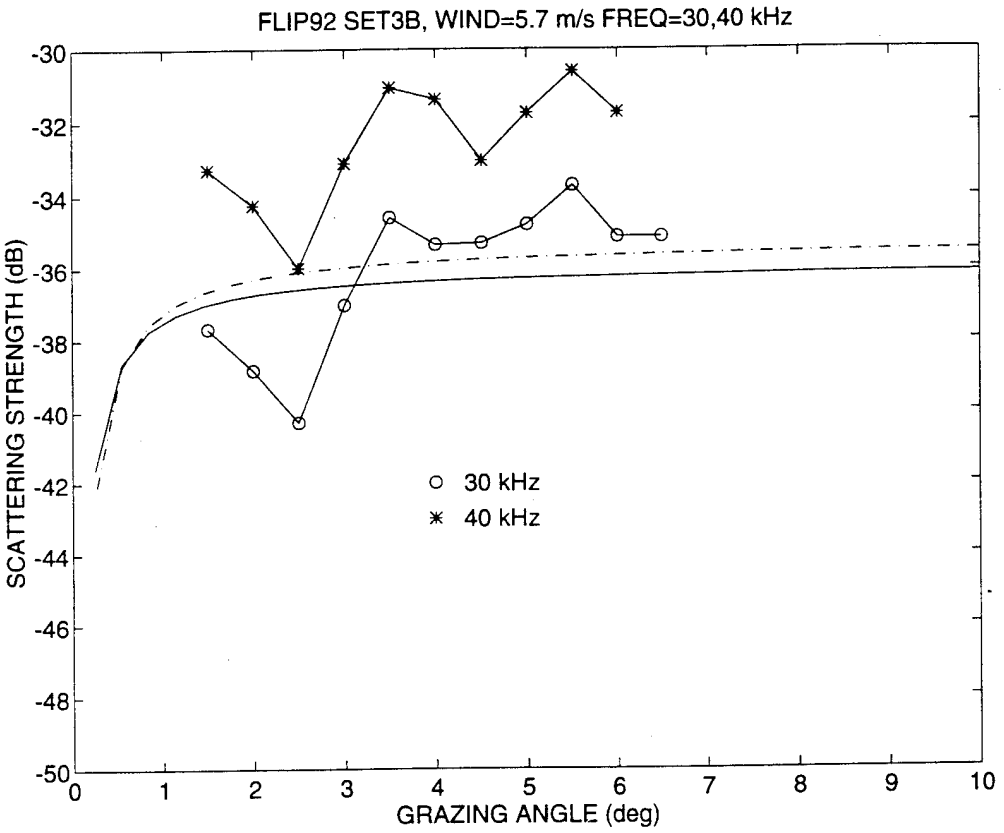

Figure 8b. Expanded scale for Figure 8a.

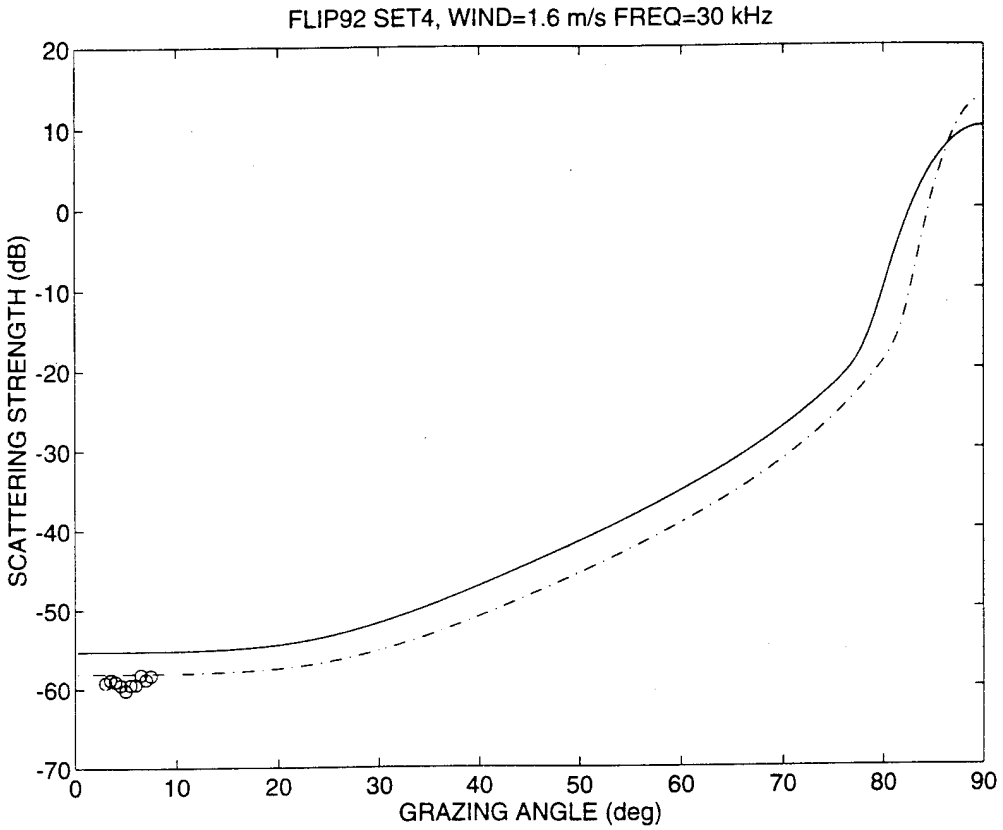

Figure 9a. Comparison of measured and modeled surface backscattering strengths at 30 kHz. Data are from one run during which the wind speed was 1.6 m/s. The solid line is the model estimate at 30 kHz for the same wind speed, and the dashed line is the model estimate for a wind speed of 1 m/s.

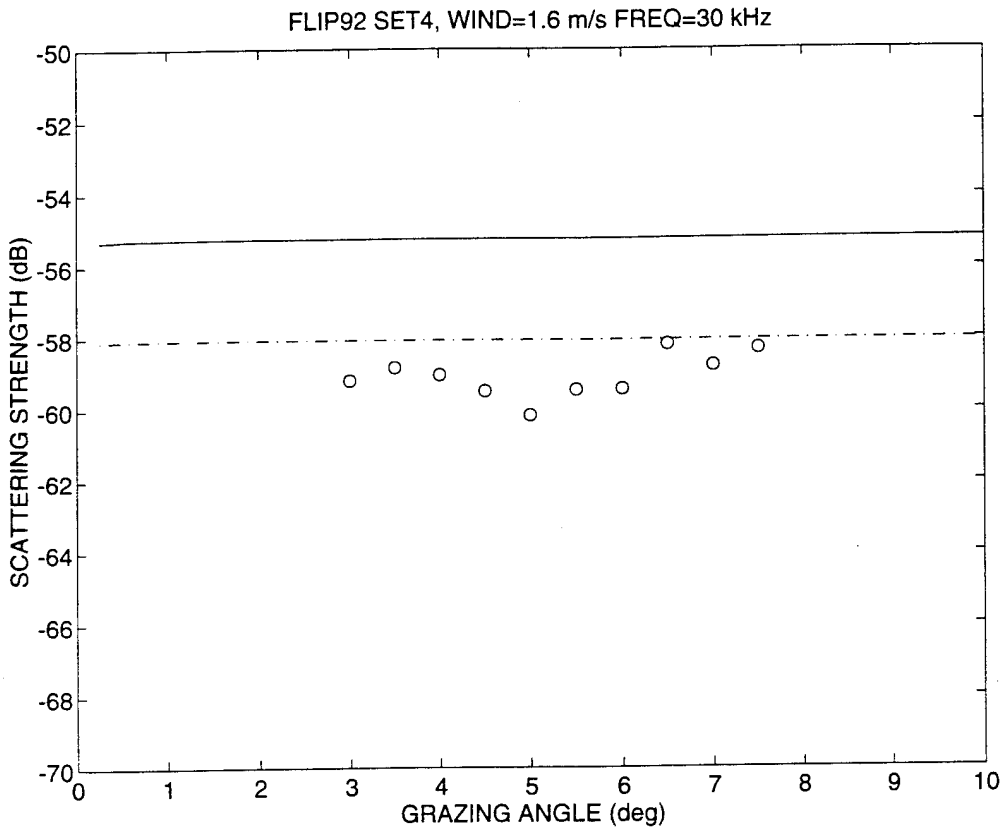

Figure 9b. Expanded scale for Figure 9a.

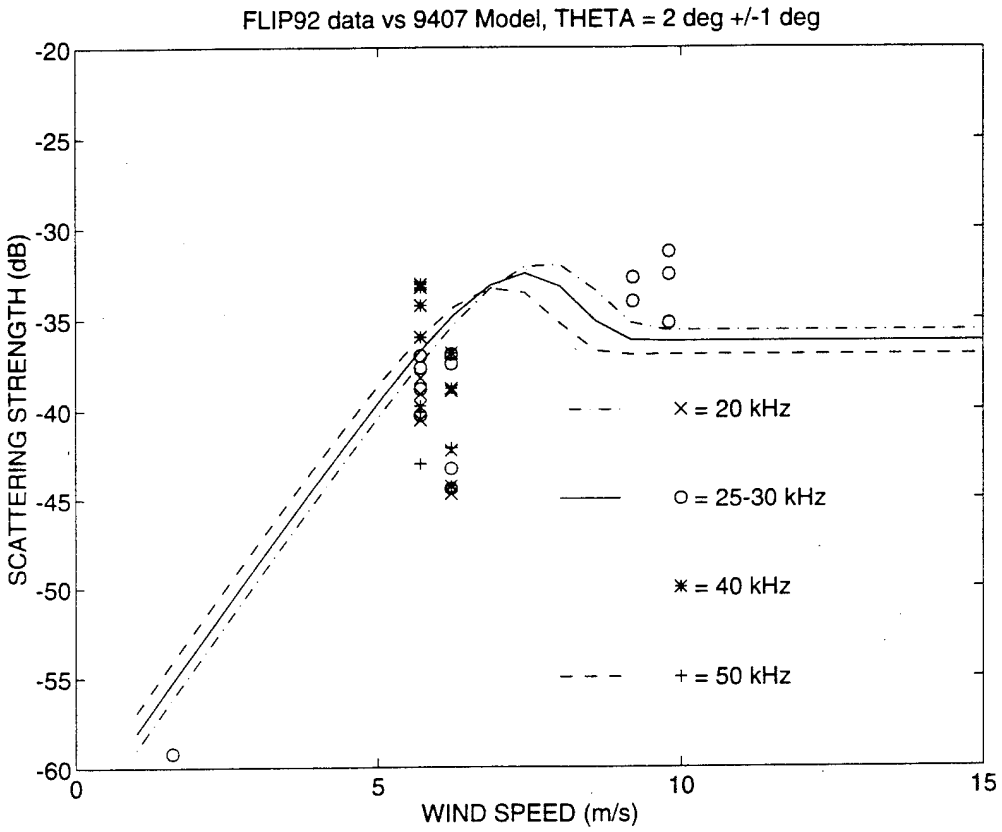

Figure 10. Comparison of measured and modeled surface backscattering strengths vs wind speed at a grazing angle of $2° \pm 1°$. Model estimates are computed at 20, 30, and 50 kHz.

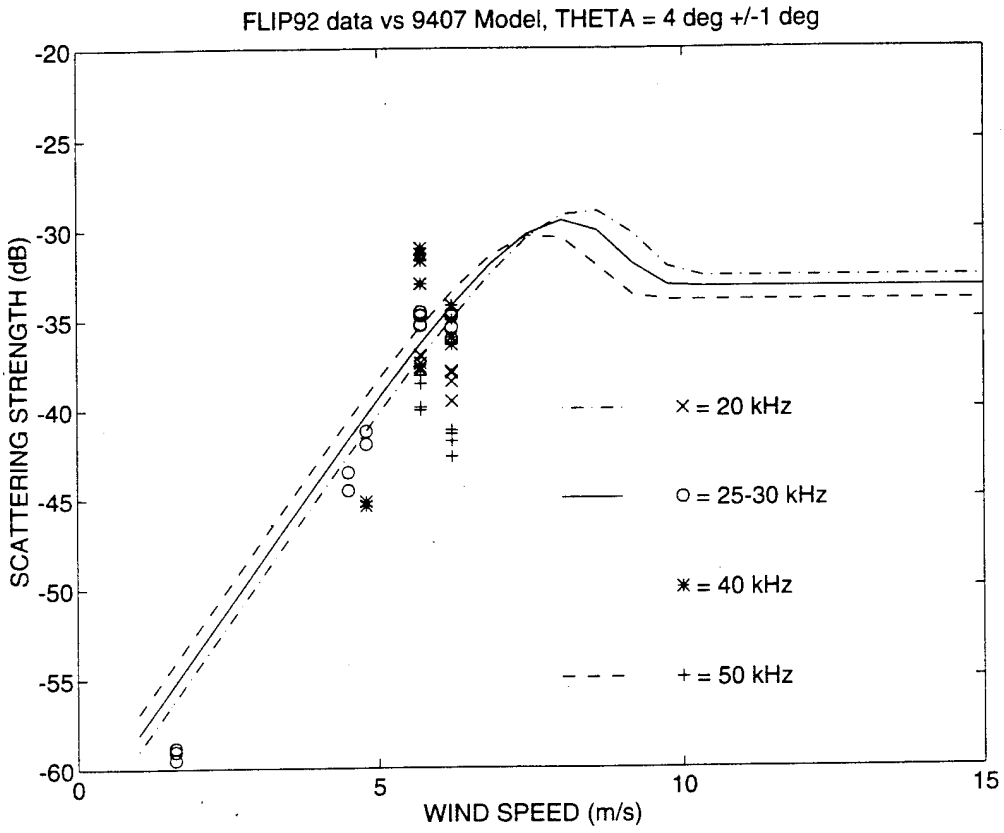

Figure 11. Comparison of measured and modeled surface backscattering strengths vs wind speed at a grazing angle of $4° \pm 1°$. Model estimates are computed at 20, 30, and 50 kHz.

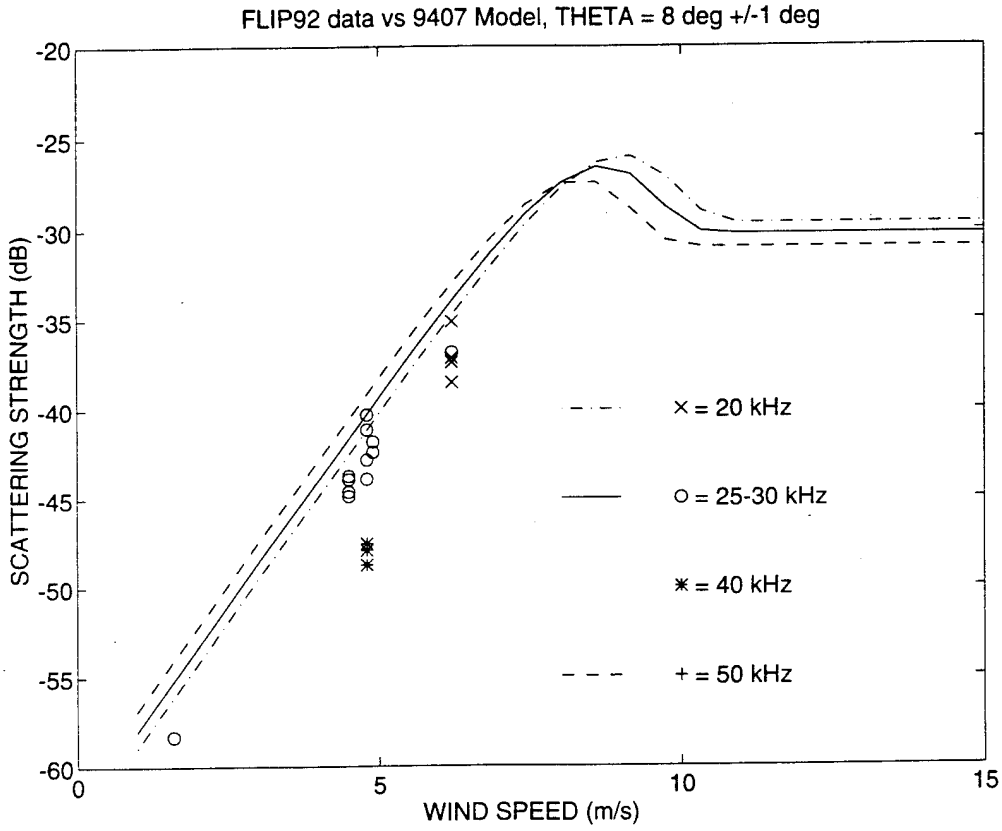

Figure 12. Comparison of measured and modeled surface backscattering strengths vs wind speed at a grazing angle of $8° \pm 1°$. Model estimates are computed at 20, 30, and 50 kHz.

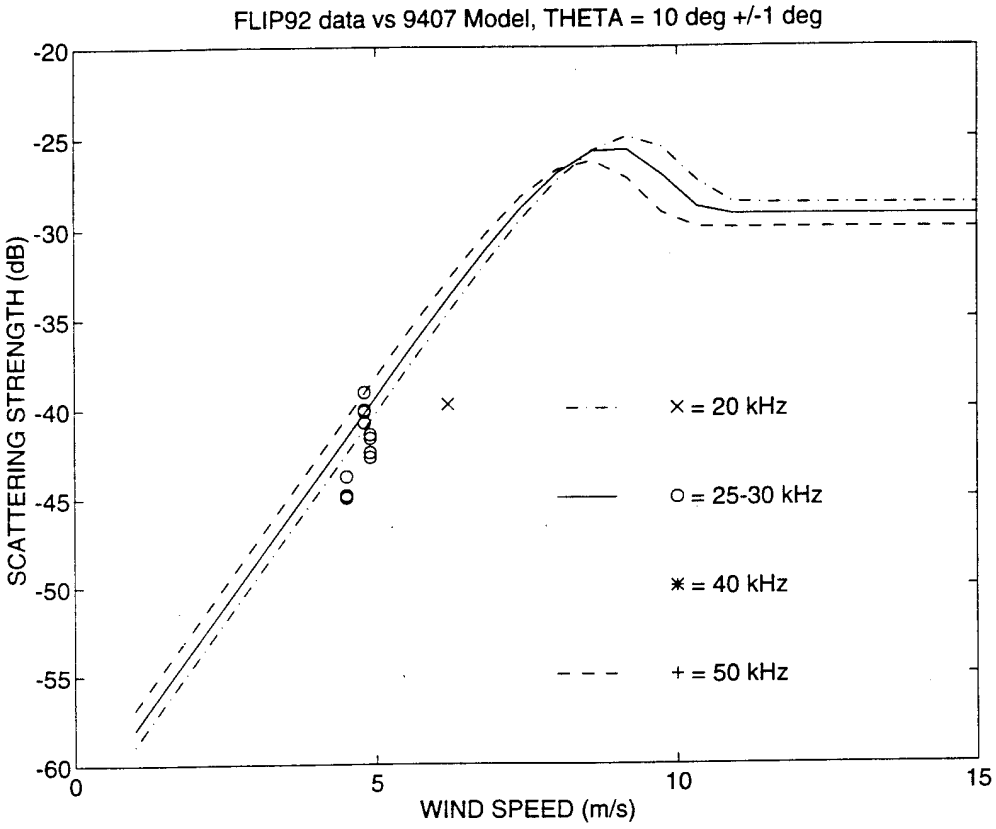

Figure 13. Comparison of measured and modeled surface backscattering strengths vs wind speed at a grazing angle of $10° \pm 1°$. Model estimates are computed at 20, 30, and 50 kHz.

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13. ABSTRACT *(Maximum 200 words)*

Several kinds of high-frequency surface-scattering measurements and environmental sea-state measurements were made from the research platform *FLIP* in January 1992. Data from this experiment continue to be used in the research and development of models that predict performance of high-frequency sonar systems. This report summarizes results of sea-surface-backscattering measurements obtained over the frequency range 20–50 kHz and the grazing-angle interval 1–15° for wind speeds between 1 and 10 m/s. This low-grazing-angle interval represents an important gap in our database of sea-surface-backscattering strength used in modeling. One data set was also obtained over the grazing-angle interval 35–55° during which the wind speed was 4.6 m/s. The data compare reasonably well with the APL-UW surface-backscattering model for the frequency range 25–40 kHz. At 20 and 50 kHz, however, the data are consistently lower (by 2–4 dB) than the model. A bias in the 20- and 50-kHz data, which is associated with the frequency response of the transducer system, is strongly suspected. Overall, the model fits the *FLIP* data to within a mean error (for the model-minus-data vector) of 1.7 dB and a standard deviation of 2.7 dB. When the 20- and 50-kHz data are corrected for bias, the mean error is reduced to 0.8 dB.

14. SUBJECT TERMS
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